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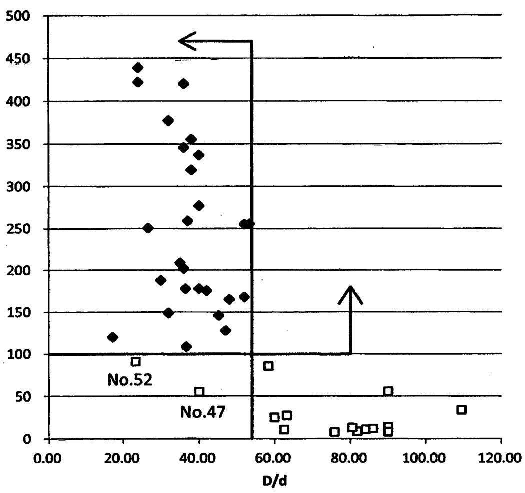
(54) STEEL MEMBER AND STEEL PLATE, AND PRODUCTION PROCESSES THEREFOR

(57) Provided is a steel member which exhibits high strength and sufficiently excellent toughness of the thicknesswise central portion even when PWHT is performed for a long time after welding. The steel member includes C, Si, Mn, P, S, Al, Cu, Ni, Cr, Mo, N, B, and V in a defined range, wherein Nb content is suppressed to 0.005% or less, Ti content is suppressed to 0.001% or less, and the total content of Ca, Mg, REM, and Zr is suppressed to 0.0010% or less, the balance being iron and inevitable impurities, and wherein a thickness is 100 mm or less, a structure in the thicknesswise central portion satisfies all the following (a) and (b), and Charpy absorbed energy at -38°C is 100 J or more: (a) a structure is at least one of tempered bainite and tempered martensite, and (b) a value represented by D/d is 54 or less, where D is an average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains, and d is a maximum diameter of grain boundary carbide.

Fig. 1



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Description

Technical Field

[0001] The present invention relates to a steel member and a steel plate and manufacturing method for them. More particularly, the present invention relates to a steel member obtained by subjecting a steel plate to welding and a post weld heat treatment (hereinafter sometimes referred to as "PWHT"), especially a steel member which is excellent in strength and low-temperature toughness of the thicknesswise central portion of the steel member even when PWHT is performed at high temperature for a long time, a steel plate used for manufacturing the steel member, and a manufacturing method for them. Hereinafter, low-temperature toughness is sometimes simply referred to as "toughness".

Background Art

[0002] There is a tendency for middle temperature/high temperature pressure vessels used in chemical industries including petroleum refining to be required to achieve higher resistance to high temperature and high pressure for the purpose of achieving high efficiency of operations. Therefore, steel plates used in steel members such as pressure vessels are required to achieve higher strength. From the viewpoint of the safety, the steel members are also required to have high-level low-temperature toughness.

[0003] To achieve higher strength, the steel plate is subjected to normalizing and quenching. However, when the steel plate has a large thickness, because of a low cooling rate of the inside, especially the thicknesswise central portion, of the steel plate during normalizing or quenching, there arises a problem that high strength is hardly obtained. By the way, the steel member such as the pressure vessel is obtained by welding the steel plate, followed by subjecting to stress relief annealing for removing strain, i.e., PWHT. To remove strain, PWHT is performed for a long time. However, the steel member subjected to PWHT for a long time has a problem that the low-temperature toughness is degraded.

[0004] The method of ensuring high toughness includes an increase in the amount of an alloy element. A Cr-Mo steel containing Cr and Mo as alloy elements is used in the steel member such as the pressure vessel. It has been known that, when using, as the Cr-Mo steel, for example, a 2.25Cr-1.0Mo steel, satisfactory toughness is obtained even in a thicknesswise central portion of a thick steel plate which hardly ensures the toughness. However, intentions towards energy saving and cost reduction have recently increased. Therefore, under the assumption of use of a Cr-Mo steel containing an alloy element in the suppressed amount compared to the 2.25Cr-1.0Mo steel, it is strongly required to realize a steel member which is excellent in strength and toughness of the thicknesswise central portion of the steel member.

[0005] There has been proposed, against the foregoing problems, the technique in which high strength and high toughness are achieved by properly adjusting chemical components while suppressing the amount of the alloy element. For example, Patent Documents 1 and 2 disclose a technique in which the low-temperature toughness is improved with respect to steels having a composition of 1.25Cr-0.5Mo level, which hardly ensure toughness.

[0006] Patent Document 1 discloses a technique in which the addition of Nb and Ca ensures the hardenability and suppresses degradation of properties during stress relief (SR) (stress relief annealing). However, when this technique is applied to a thick steel plate obtained mainly by casting using an ingot casting method, Ca may form coarse inclusions, thus exerting an adverse influence on the toughness. Therefore, it is considered to be difficult to stably ensure the toughness of the thicknesswise central portion of the thick steel member.

[0007] Patent Document 2 discloses a technique in which the austenite grains are refined by performing controlled rolling, or controlled rolling and accelerated cooling before quenching in a manufacturing process, thus ensuring low-temperature toughness. However, the controlled rolling in the technique sometimes cause degradation of a productivity of a rolling line, so that it is hardly to say that this technique is suitable for practical use.

Prior Art Document

Patent Document

[0008]

Patent Document 1: JP Hei-06-279919 A
Patent Document 2: JP 2000-345281 A

Disclosure of the Invention

Problems to be Solved by the Invention

[0009] The present invention has been made in view of the foregoing circumstances, and it is an object of the present invention to provide a steel member in which inside the steel material exhibits high strength and high low-temperature toughness even when PWHT is performed for a long time, especially at high temperature for a long time after welding in a manufacturing process of the steel method, a steel plate which is useful for the manufacture of the steel member, and a manufacturing method for them. The "inside the steel material" particularly means the "thicknesswise central portion". The same shall apply hereinafter.

Means for Solving the Problems

[0010] A steel member of the present invention, which could solve the foregoing problems, has a composition including:

C: 0.110% (% is by mass, the same shall apply hereinafter with respect to chemical components) or more and 0.15% or less,
Si: 0.50% or more and 0.80% or less,
Mn: 0.40% or more and 0.65% or less,
P: exceeding 0% and 0.0070% or less,
S: exceeding 0% and 0.0070% or less,
Al: 0.030% or more and 0.080% or less,
Cu: 0.05% or more and 0.20% or less,
Ni: 0.05% or more and 0.30% or less,
Cr: 1.05% or more 1.50% or less,
Mo: 0.45% or more and 0.65% or less,
N: 0.0030% or more and 0.0070% or less,
B: 0.0003% or more and 0.0010% or less, and
V: 0% or more and 0.030% or less,

wherein Nb content is suppressed to 0.005% or less, Ti content is suppressed to 0.001% or less, the total content of Ca, Mg, REM, and Zr is suppressed to 0.0010% or less, and the remainder consists of iron and inevitable impurities,
a thickness is 100 mm or less, and
a structure in a thicknesswise central portion of the steel member satisfies the following (a) and (b), and Charpy absorbed energy at -38°C is 100 J or more:

(a) the structure is at least one of tempered bainite and tempered martensite, and
(b) a value represented by D/d is 54 or less, where D is an average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains, and d is a maximum diameter of grain boundary carbide.

[0011] A steel plate of the present invention, which could solve the foregoing problems, is a steel plate used for manufacturing the above steel member, which has a composition including:

C: 0.110% or more and 0.15% or less,
Si: 0.50% or more and 0.80% or less,
Mn: 0.40% or more and 0.65% or less,
P: exceeding 0% and 0.0070% or less,
S: exceeding 0% and 0.0070% or less,
Al: 0.030% or more and 0.080% or less,
Cu: 0.05% or more and 0.20% or less,
Ni: 0.05% or more and 0.30% or less,
Cr: 1.05% or more 1.50% or less,
Mo: 0.45% or more and 0.65% or less,
N: 0.0030% or more and 0.0070% or less,
B: 0.0003% or more and 0.0010% or less, and
V: 0% or more and 0.030% or less,

wherein Nb content is suppressed to 0.005% or less, Ti content is suppressed to 0.001% or less, the total content of Ca, Mg, REM, and Zr is suppressed to 0.0010% or less, and the remainder consists of iron and inevitable impurities, and wherein a thickness of the steel plate is 100 mm or less.

[0012] A method for manufacturing the steel plate of the present invention, which could solve the foregoing problems, includes hot-rolling a steel slab having the above composition; performing quenching under a condition of a heating temperature of 910°C or higher and 940°C or lower and a holding time at the heating temperature of 25 minutes or more and 60 minutes or less; and, after the quenching, performing tempering at a heating temperature of 620°C or higher and an Ac_1 point or lower under a condition of the heating temperature and a heating time such that a P_T value represented by the following equation (1) is 19.2 or more and 20.6 or less:

$$P_T \text{ value} = T_T \times (20 + \log t_T) \times 10^{-3} \qquad (1)$$

where, T_T denotes heating temperature (K) of tempering, and t_T denotes heating time (hr) of tempering.

[0013] A method for manufacturing the steel member is also included in the present invention. The method for manufacturing the steel member includes welding using the above steel plate; and performing a post weld heat treatment under a condition of a heating temperature and a heating time such that a P_{PWHT} value represented by the following equation (2) is 20 or more:

$$P_{PWHT} \text{ value} = T_{PWHT} \times (20 + \log t_{PWHT}) \times 10^{-3} \qquad (2)$$

where, T_{PWHT} denotes heating temperature (K) of post weld heat treatment, and t_{PWHT} denotes heating time (hr) of post weld heat treatment.

Effects of the Invention

[0014] When the steel plate of the present invention is used in the manufacture of a steel member, it is possible to obtain a steel member in which inside the steel material exhibits high strength and sufficiently excellent toughness even when PWHT is performed for a long time, especially at high temperature for a long time after welding in the manufacturing process of the steel member. As a result, it is possible to provide middle temperature/high temperature pressure vessels which exhibit high strength and high toughness.

[0015] Furthermore, the steel member of the present invention contributes to energy saving and cost reduction since the alloy element amount is suppressed.

Brief Description of the Drawings

[0016] Fig. 1 is a graph showing the relationship between D/d and Charpy absorbed energy at -38°C in Examples.

Mode for Carrying Out the Invention

[0017] The inventors have intensively studied so as to obtain a steel member which is excellent in low-temperature toughness and strength of the thicknesswise central portion of the steel member even when the steel member is manufactured by subjecting a steel plate to PWHT especially for a long time under the assumption of use of the steel plate formed of a Cr-Mo steel whose alloy element amount is suppressed compared to the 2.25Cr-1.0Mo steel.

[0018] As a result, it has been found that, to obtain the steel member whose thicknesswise central portion has high toughness, a fine microstructure is formed, and refining of grain boundary carbide, which easily undergoes coarsening and serves as a fracture origin, is performed. In detail, (a) a structure is made to be at least one of tempered bainite and tempered martensite, and (b) a value represented by D/d is set at 54 or less, where D is an average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains, and d is a maximum diameter of grain boundary carbide; and temper embrittlement sensitivity is suppressed, specifically, the below-mentioned composition is made to be satisfied. Hereinafter, the "average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains" is sometimes simply referred to as "large angle grain boundary size". The "suppression of temper embrittlement sensitivity" is also referred to as "suppression of temper embrittlement" or "suppression of intergranular cracks".

[0019] First, the above-mentioned (a) and (b) with respect to a microstructure of the thicknesswise central portion of the steel member of the present invention will be described.

[0020] In the following description, "structure of thicknesswise central portion" is simply referred to as "structure". The below-mentioned properties, i.e., strength and low-temperature toughness mean properties of at least thicknesswise central portion of the steel member, i.e., after subjecting a steel plate to welding and PWHT.

(a) A structure is at least one of tempered bainite and tempered martensite.
The tempered bainite and tempered martensite are fine structures and are structures which are particularly effective in ensuring the strength and toughness of the thicknesswise central portion. The steel member of the present invention has a structure which is at least one of tempered bainite and tempered martensite. Examples of the other structure, which can be inevitably included, include polygonal ferrite, retained austenite, pearlite, and the like. The total area % of these structures is suppressed to 5 area % or less, and most preferably 0 area %. Particularly, when the polygonal ferrite exists, the structure is mainly an upper bainite structure having a large crystal grain size, thus failing to ensure satisfactory toughness.
(b) A value represented by D/d is 54 or less, where D is an average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains, and d is a maximum diameter of grain boundary carbide.

[0021] When the structure of the thicknesswise central portion is made to be at least one of tempered bainite and tempered martensite, as mentioned above, the structure can be refined. However, in the present invention, the above-mentioned (b) is defined so as to obtain high toughness by reliable refining of the structure.

[0022] In the case of the structure of tempered bainite and tempered martensite, so-called large angle grain boundaries in which misorientation (crystal misorientation) between two adjacent crystal grains is 15° or more generally exhibit large misorientation between two adjacent crystal grains. Therefore, the progress of brittle fracture is curved and the fracture surface unit of brittle fracture decreases, thus contributing to an improvement in toughness. Meanwhile, the steel member of the present invention is subjected to PWHT, especially PWHT for a long time, more especially PWHT at high temperature for a long time, as mentioned above. When the Cr-Mo steel constituting the steel member is subjected to PWHT, grain boundary carbide $M_{23}C_6$ is generally formed. When the condition of the PWHT becomes severe condition at high temperature for a long time, the grain boundary carbide easily undergoes coarsening and serves as a fracture origin, causing degradation of the toughness.

[0023] In the present invention, it has been found that, if a value represented by D/d satisfies 54 or less, as mentioned in the above (b), with respect to the relationship between an average equivalent circle diameter D in terms of the large angle grain boundary size and a maximum diameter d of the grain boundary carbide, it is possible to ensure sufficiently excellent toughness even after PWHT. The above-mentioned D/d is preferably 50 or less, and more preferably 48 or less. Considering the composition, manufacturing conditions and the like defined in the present invention, the lower limit value of D/d is about 12.

[0024] In the present invention, D/d may satisfy 54 or less, and there is no particular limitation on each value of the average equivalent circle diameter D of large angle grain boundaries and the maximum diameter d of the grain boundary carbide. The average equivalent circle diameter D of large angle grain boundaries can be set at, for example, 45 μm or less, 35 μm or less, 30 μm or less, 25 μm or less, and 15 μm or less. The lower limit of the average equivalent circle diameter D of large angle grain boundaries is approximately 10 μm from a manufacturing point of view. The maximum diameter d of the grain boundary carbide can be set at, for example, 0.8 μm or less. The maximum diameter d of the grain boundary carbide can also be set at 0.70 μm or less, and 0.60 μm or less. The lower limit of the maximum diameter d of the grain boundary carbide is approximately 0.20 μm in the range of the composition and manufacturing conditions defined in the present invention.

[0025] In the present invention, there is a need to control the structure of the thicknesswise central portion as mentioned above, and there is no particular limitation on the structure of other parts, for example, a thickness surface layer part. In the part which exists at the surface layer side from the thicknesswise central portion, a cooling rate during quenching is generally higher than that in the thicknesswise central portion, so that it is easy to obtain a fine structure compared to the thicknesswise central portion, and both strength and toughness tend to be more improved compared to the thicknesswise central portion.

[0026] In the thicknesswise central portion, to obtain a fine structure of the above-mentioned (a) and (b), there is a need to particularly make the composition of a steel plate used in the manufacture of the steel member composition to be mentioned below. To decrease the average equivalent circle diameter D such that the above-mentioned D/d is satisfy 54 or less, there is a need to enhance the hardenability by including B in the below-mentioned amount leading to the existence as free B (solid-soluted B). It is important that N capable of easily combining with B to form BN is fixed as AlN by adding Al in the below-mentioned amount, in order to ensure free B. This AlN is useful for suppressing coarsening of prior austenite (γ) grains during quenching to obtain a fine structure.

[0027] To decrease the average equivalent circle diameter D, it is effective to improve the hardenability by adding the alloy element, as mentioned above. Excessive C, excessive Cu, and excessive Ni increase the strength more than necessary, causing degradation of the toughness. Therefore, there is a need to set the upper limit of C, Cu, and Ni from the viewpoint of ensuring toughness.

[0028] In the present invention, each content of Nb and Ti is suppressed. The reason is that inclusion of a large amount of these elements makes it difficult to achieve D/d in the above range. These elements also increase the strength more than necessary, causing degradation of workability. Furthermore, a total content of Ca, Mg, REM, and Zr is also suppressed. The reason is that these elements increase inclusions, causing degradation of the toughness. To control the size of the grain boundary carbide, there is also a need to control the content of Cr, in addition to C. To ensure the toughness by suppressing temper embrittlement sensitivity, there is also a need to control the content of Si.

[0029] As mentioned in detail below, it is important to properly control, as manufacturing conditions, conditions of quenching and tempering during the manufacture of a steel plate to be subjected to welding.

[0030] First, the composition of a steel plate and a steel member required to ensure the structure and properties will be described.

C: 0.110% or more and 0.15% or less

[0031] C is an element which is required to obtain at least one of tempered bainite and tempered martensite during quenching of a steel plate even in the thicknesswise central portion with a low cooling rate, and to decrease the average grain size D by enhancing hardenability thereby setting D/d in the above range. It is also an element which is required to obtain sufficient base material strength by ensuring the grain boundary carbide. To sufficiently exert these effects, the C content is set at 0.110% or more. The C content is preferably 0.120% or more, and more preferably 0.130% or more. However, excessive C content causes coarsening of grain boundary carbide after PWHT for a long time, leading to degradation of the toughness. During welding of a steel plate, weld cracks easily occur. Therefore, the C content is set at 0.15% or less. The C content is preferably 0.145% or less.

Si: 0.50% or more and 0.80% or less

[0032] Si is an element which is effective in improving the base material strength of a steel member, i.e., the strength of the thicknesswise central portion. It is also an element to be used as a deoxidizing agent. It is also an element useful for suppressing temper embrittlement sensitivity, thereby ensuring the toughness. To exert these effects, the Si content is set at 0.50% or more. The Si content is preferably 0.55% or more, and more preferably 0.60% or more. However, excessive Si content enhances temper embrittlement sensitivity, leading to degradation of the toughness, so that the Si content is set at 0.80% or less. The Si content is preferably 0.75% or less, and more preferably 0.70% or less.

Mn: 0.40% or more and 0.65% or less

[0033] Mn is an element which is effective in improving the hardenability by stabilizing austenite and achieving lowering of the transformation temperature to obtain a fine structure, thus ensuring the strength and toughness. To exert these effects, 0.40% or more of Mn is contained. The Mn content is preferably 0.45% or more, and more preferably 0.46% or more. However, excessive Mn content enhances temper embrittlement sensitivity, leading to degradation of the toughness. Therefore, the Mn content is 0.65% or less, preferably 0.60% or less, more preferably 0.55% or less, and still more preferably 0.50% or less.

P: exceeding 0% and 0.0070% or less

[0034] P as an inevitable impurity exerts an adverse influence on the toughness of a base material and the weld zone, and is particularly segregated on grain boundaries of a steel member, thus causing intergranular cracks, leading to degradation of the toughness. To prevent these disadvantages, the P content is suppressed to 0.0070% or less. The P content is preferably 0.0060% or less, and more preferably 0.0050% or less.

S: exceeding 0% and 0.0070% or less

[0035] S is an element which easily forms MnS, causing weld cracks during welding of a steel plate. Therefore, the S content is preferably as small as possible, and the S content is suppressed to 0.0070% or less, preferably 0.0050% or less, and more preferably 0.0030% or less.

Al: 0.030% or more and 0.080% or less

[0036] Al is a very important element in the present invention, as mentioned above, and is an element required to fix N as AlN during quenching and to ensure the hardenability due to free B. AlN is useful for suppressing coarsening of prior austenite (γ) grains during quenching to obtain a fine structure. Al is also an element required for deoxidation. To exert these effects, the Al content is set at 0.030% or more. The Al content is preferably 0.040% or more, more preferably 0.045% or more, and still more preferably 0.050% or more. Meanwhile, excessive Al content enables formation of alumina-based coarse inclusions, causing degradation of the toughness. Therefore, the Al content is set at 0.080% or less. The Al content is preferably 0.075% or less, and more preferably 0.071% or less.

Cu: 0.05% or more and 0.20% or less, Ni: 0.05% or more and 0.30% or less

[0037] Cu and Ni are elements which are effective in increasing the strength without significantly impairing the toughness. To sufficiently exert this effect, 0.05% or more, preferably 0.10% or more, and more preferably 0.11% or more of Cu is contained, and 0.05% or more, preferably 0.10% or more, more preferably 0.15% or more, and still more preferably 0.16% or more of Ni is contained. The addition of a large amount of these elements increases the strength more than necessary, as mentioned above, causing degradation of the toughness. Therefore, the upper limit of the Cu content is set at 0.20% or less, and the upper limit of the Ni content is set at 0.30% or less. The Cu content is preferably 0.18% or less, and more preferably 0.17% or less. The Ni content is preferably 0.28% or less, and more preferably 0.26% or less.

Cr: 1.05% or more and 1.50% or less

[0038] Cr is an element which is effective in suppressing coarsening of carbide due to PWHT, thereby ensuring the toughness of a steel member. It is also an element which is effective in ensuring the strength in middle temperature/high temperature region and improving the corrosion resistance. To exert these effects, 1.05% or more of Cr is contained. The Cr content is preferably 1.10% or more, and more preferably 1.20% or more. Meanwhile, if Cr is contained excessively, temper embrittlement sensitivity is easily enhanced after PWHT, causing intergranular cracks, leading to exert an adverse influence on the toughness. Excessive Cr causes degradation of the workability and weldability, and an increase in manufacturing cost. Therefore, the Cr content is set at 1.50% or less. The Cr content is preferably 1.45% or less, and more preferably 1.40% or less.

Mo: 0.45% or more and 0.65% or less

[0039] Mo is an element which is effective in enhancing the hardenability and suppressing temper embrittlement. To obtain these effects, there is a need to contain 0.45% or more of Mo. The Mo content is preferably 0.50% or more, and more preferably 0.55% or more. Meanwhile, the effect is scarcely improved even when the Mo content exceeds 0.65%, leading to an increase in manufacturing cost, so that the upper limit of the Mo content is set at 0.65% or less. The Mo content is preferably 0.62% or less.

N: 0.0030% or more and 0.0070% or less

[0040] N is an important element in the present invention, along with Al. By forming AlN to fix N during quenching, the hardenability improving effect due to free B can be maximized. AlN is useful for suppressing coarsening of prior austenite (γ) grains during quenching to obtain a fine structure. If the N content is less than 0.0030%, coarsening of austenite (γ) grain occurs due to lack of AlN, thus failing to obtain a fine structure, leading to degradation of the toughness. Therefore, the N content is set at 0.0030% or more. The N content is preferably 0.0035% or more, and more preferably 0.0040% or more. Meanwhile, if the N content exceeds 0.0070%, the N-fixing effect due to Al cannot be obtained and BN is formed. Therefore, the hardenability improving effect due to free B is suppressed, causing coarsening of the structure, leading to degradation of the toughness. Therefore, the N content is set at 0.0070% or less. The N content is preferably 0.0060% or less, more preferably 0.0055% or less, and still more preferably 0.0050% or less.

B: 0.0003% or more and 0.0010% or less

[0041] As mentioned above, the existence of B as free B (solid-soluted B) enhances the hardenability, thus making it possible to decrease the average grain size D even in the thicknesswise central portion of a thick steel plate which is cooled at a low cooling rate during quenching. As a result, it is possible to ensure excellent toughness even in the thicknesswise central portion. To obtain such effect, 0.0003% or more of B is required even under the assumption of controlling the above-mentioned contents of Al and N, and quenching conditions. The B content is preferably 0.0005%

or more, and more preferably 0.0007% or more. Meanwhile, if B is contained excessively, the hardenability may be degraded, or weld cracks may occur, so that the upper limit of the B content is set at 0.0010%. The B content is preferably 0.0009% or less, and more preferably 0.0008% or less.

V: 0% or more and 0.030% or less

[0042] V is an element which is effective in forming carbide and nitride, thereby contributing to an improvement in strength, and enhancing the hardenability to obtain a fine structure. To obtain these effects, 0.003% or more of V may be preferably contained. The V content is more preferably 0.005% or more. Meanwhile, excessive addition of V causes an increase in cost, so that the upper limit is set at 0.030% or less. The V content is preferably 0.027% or less, more preferably 0.020% or less, and still more preferably 0.010% or less.

Nb content is 0.005% or less, Ti content is 0.001% or less, and the total content of Ca, Mg, REM, and Zr is 0.0010% or less

[0043] In the present invention, Nb content is suppressed to 0.005% or less, Ti content is suppressed to 0.001% or less, and the total content of Ca, Mg, rare earth metal (REM), and Zr is suppressed to 0.0010% or less. As mentioned above, Nb and Ti refine prior austenite (γ) grains during quenching, leading to degradation of the hardenability. As a result, the large angle grain boundary size increases, i.e., the average equivalent circle diameter D increases, so that D/d exceeds a defined range. Nb and Ti are elements which increase the strength more than necessary, leading to degradation of the workability. Furthermore, Ca, Mg, REM, and Zr increase inclusions, leading to degradation of the toughness. As is apparent from the above, the contents of these elements are preferably suppressed as small as possible, and the content of any element may be zero. In the present invention, REM means that lanthanoid elements, i.e., fifteen elements from La to Lu, and scandium and yttrium are included.

[0044] The steel plate and the steel member of the present invention include the above-mentioned chemical components, with the balance being iron and inevitable impurities.

[0045] Next, a method for manufacturing the steel plate and the steel member of the present invention will be described. First, a method for manufacturing the steel plate will be described.

[0046] A steel slab having the above-mentioned composition is hot-rolled by a conventional method to obtain a steel plate, and then the steel plate is subjected to quenching and tempering. To obtain a fine structure defined in the above-mentioned (a) and (b) of a steel member, there is a need to perform quenching and tempering in the manufacturing process of a steel plate under the following conditions.

[0047] Heating temperature of quenching: 910°C or higher and 940°C or lower, and holding time at the heating temperature: 25 minutes or more and 60 minutes or less

[0048] By setting the heating temperature of quenching at 910 to 940°C and setting the heat holding time at 25 minutes or more, prior austenite (γ) grains can be allowed to grow to some extent, thus improving the hardenability to obtain a fine structure.

[0049] If the heating temperature of quenching is lower than 910°C, prior austenite (γ) grains during quenching keep fine grain size. Therefore, a fine structure cannot be obtained in the portion with a low cooling rate, such as the thicknesswise central portion of the steel plate, thus failing to ensure excellent toughness. Therefore, the heating temperature of quenching is set at 910°C or higher. The heating temperature is preferably 920°C or higher. Meanwhile, if the heating temperature exceeds 940°C, N fixed as AlN is partially solid-soluted and combined with B to form BN, thus failing to obtain the hardenability improving effect due to free B. As a result, a fine structure cannot be obtained, leading to degradation of the toughness. Therefore, the heating temperature of quenching is set at 940°C or lower. The heating temperature is preferably 935°C or lower.

[0050] Even when the heating temperature during quenching is in the above range, prior austenite (γ) grains keep fine grain size if the holding time at the heating temperature (heat holding time) is shorter than 25 minutes. Therefore, sufficient hardenability cannot be obtained even when a predetermined amount of B is contained, thus causing coarsening of the structure, leading to degradation of the toughness. Therefore, the heat holding time is set at 25 minutes or more. The heat holding time is preferably 30 minutes or more. From the viewpoint of the productivity, the upper limit of the heat holding time is 60 minutes or less, and preferably 55 minutes or less.

[0051] It is preferred that the prior austenite (γ) grain diameter is adjusted in a range of about 50 to 100 μm by controlling the conditions during quenching as mentioned above, because it is easy to obtain a fine structure.

[0052] Subsequently to the above quenching, tempering is performed at a temperature of 620°C or higher and an Ac_1 point or lower under a condition of the heating temperature and a heating time such that a P_T value represented by the following equation (1) is 19.2 or more and 20.6 or less:

$$P_T \text{ value} = T_T \times (20 + \log t_T) \times 10^{-3} \qquad (1)$$

where, T_T denotes heating temperature (K) of tempering, and t_T denotes heating time (hr) of tempering.

[0053] Heating temperature of tempering (tempering temperature) : 620°C or higher and an Ac_1 point or lower

[0054] In the above quenching, because of a high cooling rate in the vicinity of a surface layer regardless of the thickness, a hardness of the surface layer easily increases. Therefore, after quenching, tempering is performed, thus enabling an improvement in workability such as bending of the steel plate. Therefore, in the manufacturing process of a steel member, tempering is performed to reduce the hardness of the surface layer from the viewpoint of improving the workability of the steel plate. Tempering is performed under the condition of the tempering temperature of 620°C or higher and an Ac_1 point or lower. By setting the tempering temperature at 620 °C or higher, the hardness of the surface layer is sufficiently reduced, thus making it possible to ensure satisfactory workability. The tempering temperature is preferably 700°C or higher. Meanwhile, if the tempering temperature exceeds the Ac_1 point, the structure partially undergoes reverse transformation and then air-cooled, leading to intermixing of polygonal ferrite. As a result, at least one of tempered bainite and tempered martensite as a desired structure cannot be obtained, leading to a decrease in strength, and degradation of the toughness because the reversely transformed portion has a coarse structure. Therefore, the upper limit of the tempering temperature is set at the Ac_1 point or lower. The tempering temperature is preferably 750°C or lower. The Ac_1 point can be determined by the method in the below-mentioned Examples.

[0055] Tempering is performed under the condition of the heating temperature and the heating time such that a P_T value represented by the defined equation (1) is within the above ranges. If the P_T value is less than 19.2, the hardness increases excessively, causing defects such as degradation of the workability. Therefore, the P_T value is 19.2 or more, preferably 19.3 or more, and more preferably 19.4 or more. Meanwhile, if the P_T value exceeds 20.6, coarsening of carbide occurs, causing degradation of properties such as toughness. Therefore, the P_T value is 20.6 or less, preferably 20.3 or less, and more preferably 20.0 or less.

[0056] The steel plate of the present invention has a thickness of 100 mm or less. The lower limit of the thickness is 6 mm or more, and 10 mm or more. The steel member obtained by using the steel plate also has the same thickness as that of the steel plate.

[0057] The steel member of the present invention is obtained by welding the steel plate obtained by subjecting to the quenching and tempering, using a common method, followed by subjecting to the post weld heat treatment (PWHT) for removal of strain as mentioned above.

[0058] The method for manufacturing the steel member of the present invention is characterized in that the post weld heat treatment is performed under a condition of a heating temperature and a heating time such that a P_{PWHT} value represented by the following equation (2) is 20 or more. The condition indicates severe condition at high temperature for a long time (e.g., when the temperature is 680°C or higher and the heating time is 20 hours or more, a P_{PWHT} value is 20.3). In the present invention, even after subjected to a heat treatment under such severe condition at high temperature for a long time, a steel member having sufficiently excellent toughness can be obtained. The upper limit of the P_{PWHT} value is approximately 21. The condition of PWHT includes, for example, the condition of a heating temperature of 600 to 690°C and heating time of 5 hours to 22 hours:

$$P_{PWHT} \text{ value} = T_{PWHT} \times (20 + \log t_{PWHT}) \times 10^{-3} \qquad (2)$$

where, T_{PWHT} denotes heating temperature (K) of post weld heat treatment, and T_{PWHT} denotes heating time (hr) of post weld heat treatment.

[0059] The steel member of the present invention can be used, for example, as middle temperature/high temperature pressure vessels used in chemical industries including petroleum refining.

[0060] This application claims priority based on Japanese Patent Application No. 2015-218435 filed on November 6, 2015, the disclosure of which is incorporated by reference herein.

Examples

[0061] The present disclosure will be more specifically described below by way of Examples but is not limited to the following Examples. Various modifications can be made to these examples as long as they are adaptable to the above-mentioned and below-mentioned concepts and are included within the technical scope of the present disclosure.

[0062] Each of steel slabs satisfying the compositions shown in Table 1-1 and Table 1-2 was hot-rolled by a conventional method and then subjected to quenching and tempering under the conditions shown in Table 2-1 and Table 2-2 to obtain steel plates each having a thickness shown in Table 2-1 and Table 2-2. The thickness is also the thickness of a specimen that simulates a steel member. Each of Ac_1 points shown in Table 2-1 and Table 2-2 was determined by analyzing a change in expansion rate when heated at a temperature rising rate of 0.5°C/sec using steel plates each having the composition shown in Table 1-1 and Table 1-2. The heating temperature of quenching and tempering is the temperature in the thicknesswise central portion of the steel plate, and is the temperature obtained by calculating from the furnace atmospheric temperature and the in-furnace time of a heat treatment furnace using a difference method, or the temperature measured by inserting a thermocouple into a dummy material having the same thickness when using an experimental furnace.

[0063] Furthermore, using a truck-type electric furnace in an air atmosphere, a heat treatment was performed by simulating PWHT after welding under the condition of the heating temperature of 690°C and the heat holding time of 22 hours to obtain a specimen that stimulates a steel member. The condition is the most severe conditions among conditions that are currently being carried out. In this case, the P_{PWHT} value is 20.6. Both a temperature rising rate from room temperature to the heating temperature, and a temperature falling rate from the heating temperature to room temperature were set at 55°C/hr or less.

[0064] When the steel member is manufactured, the steel plate is subjected to PWHT after welding. After multilayer welding was performed as the welding, the welding scarcely exerts an adverse influence on properties, especially toughness, of a steel member including the welded heat affected zone, so that a specimen was fabricated without subjecting to a heat treatment with respect to welding in the present example.

[0065] Using the specimen thus obtained, evaluation of metal structure, a tensile test, and a Charpy impact test were carried in accordance with the following procedures. To evaluate the workability of the steel plate, which is the property required in the manufacturing process of a steel member, surface layer hardness was measured using a steel plate before subjecting to PWHT.

[Observation of metal structure]

[0066] The metal structure was observed in the following manner.

(1) To enable observation of a thickness cross section including front and rear surfaces of a steel plate, which is parallel to the rolling direction and is perpendicular to a surface of the steel plate, samples were taken from the steel plate.
(2) Using a method of polishing such as polishing with a wet emery polishing paper (#150 to #1000) or polishing with an abrasive such as diamond slurry having the same function as that of the above polishing, mirror finishing of an observation surface was performed.
(3) The polished sample was etched with a 3% nital solution, thereby allowing crystal grain boundaries to appear.
(4) In the t (thickness)/2 portion, the structure appeared was photographed at a magnification of 400 times. In the present example, photographing was performed as a micrograph in size of 6 cm $\times$ 8 cm. In the thus obtained micrograph, the region where polygonal ferrite is formed on prior austenite (γ) grain boundaries was discriminated, followed by filling with black color. Next, the micrograph was captured in an image analyzer. In the case of a magnification of 400 times, the region of the micrograph corresponds to 150 μm $\times$ 200 μm. In the case of any magnification, the micrograph was captured in an image analyzer such that the total of the region is 1 mm $\times$ 1 mm or more. In the case of 400 times, at least 35 micrographs were captured.
(5) In the image analyzer, a black area ratio was calculated every micrograph and an average of all micrographs was regarded as a polygonal ferrite (F) fraction, and the remainder after deducting the polygonal ferrite (F) fraction from the whole area ratio was regarded as a fraction of at least one of tempered bainite and tempered martensite (B+M).

[0067] The tempered bainite as used herein refers to a structure in which upper bainite, lower bainite, bainitic ferrite or the like is tempered. It is generally difficult to select these structures including tempered martensite, and the structure is sufficiently tempered after PWHT. Therefore, the structure other than polygonal ferrite was regarded as at least one of tempered bainite and tempered martensite (B+M). - It was also confirmed that pearlite structure is not contained in any specimen used in the present example.

[Measurement of large angle grain boundary size by electron back scattering pattern (EBSP) method]

[0068] Using an EBSP method, an average equivalent circle diameter (large angle grain boundary size) of crystal grains surrounded by large angle grain boundaries with misorientation (crystal misorientation) of 15° or more between two adjacent crystal grains was determined. The measurement procedure was as follows.

(1) To enable observation of a thickness cross section including front and rear surfaces of a steel plate, which is

parallel to the rolling direction and is perpendicular to a surface of the steel plate, samples were taken from the steel plate.
(2) Using a method of polishing with a wet emery polishing paper (#150 to #1000) or polishing having the same function as that of the above polishing (polishing with an abrasive such as diamond slurry), mirror finishing of an observation surface was performed.
(3) Using an EBSP apparatus manufactured by TexSEM Laboratories Inc., the size of crystal grains (large angle grains) surrounded by crystal grain boundaries was measured under the assumption of regarding, as a crystal grain boundary, boundary in which the crystal misorientation is 15° or more in the t (thickness)/2 portion of the thickness direction within a measuring range of 200 × 200 μm and 0.5 μm pitch. Data of measurement points having a confidence index, indicating the reliability of measurement orientation, of less than 0.1 were excluded from objects to be analyzed.
(4) An average of the thus obtained size of crystal grains surrounded by large angle grain boundaries was calculated and regarded as the "average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains" in the present invention. Crystal grains having grain sizes of 1.0 μm or less surrounded by large angle grain boundaries were determined as measurement noise and were excluded from the calculation of average grain size.

[Measurement of size of grain boundary carbide]

[0069] The size of grain boundary carbide was measured as follows.

(1) To enable observation of a thickness cross section including front and rear surfaces of a steel plate, which is parallel to the rolling direction and is perpendicular to a surface of the steel plate, samples were taken from the steel plate.
(2) Using a method of polishing with a wet emery polishing paper (#150 to #1000) or polishing having the same function as that of the above polishing (polishing with an abrasive such as diamond slurry), mirror finishing of an observation surface was performed.
(3) The polished sample was etched with a 3% nital solution, thereby allowing crystal grain boundaries to appear.
(4) In the t (thickness)/2 portion, the structure appeared was photographed at a magnification of 1,000 times. In the present example, photographing was performed as a micrograph in size of 6 cm × 8 cm. Next, the micrograph was captured in an image analyzer. In the case of a magnification of 1,000 times, the region of the micrograph corresponds to 60 μm × 80 μm. The micrograph was captured in an image analyzer such that the total of the region is 0.4 mm × 0.4 mm or more. In the case of 1,000 times, at least 35 micrographs were captured.
(5) In the image analyzer, the short axis length was calculated as the size of grain boundary carbide every micrograph, and a maximum value of the grain boundary carbide size of all micrographs was calculated.

[Tensile test (evaluation of tensile properties)]

[0070] Round bar tensile specimens were taken in the direction perpendicular to the rolling direction from the t (thickness)/2 portion and a tensile test was performed in accordance with the procedure of ASTM A370, and then the yield strength and the tensile strength were measured. The case where YS as the yield strength is 310 MPa or more and TS as the tensile strength is 515 MPa or more was rated as high strength.

[Charpy impact test (evaluation of impact properties)]

[0071] Full-sized V-notched specimens were taken in the direction perpendicular to the rolling direction from the t (thickness)/2 portion and a Charpy impact test was performed at a test temperature of -38°C in accordance with the procedure of ASTM A370, and then the Charpy absorbed energy was measured. An average of Charpy absorbed energy of three specimens was employed. The case where the Charpy absorbed energy at -38°C, vE_{-38}, is 100 J or more was rated as excellent toughness, i.e. excellent impact properties.

[Measurement of surface layer hardness (evaluation of workability of steel plate)]

[0072] To evaluate the workability of a steel plate, using the steel plate before subjecting to PWHT, a Brinell hardness test was performed in a position at a depth of 1 mm from a surface in accordance with the procedure of ASTM A370. The case where the average of HBW is 200 or less was rated as excellent workability, while the case where the average of HBW exceeds 200 was rated as ordinary workability.
[0073] These results are shown in Table 3-1 and Table 3-2. The following Nos. indicate test Nos. of Table 2-1, Table 2-2, Table 3-1, and Table 3-2.

[Table 1-1]

Symbol of steel type	Composition (% by mass) Balance being iron and inevitable impurities														
	C	Si	Mn	P	S	Al	Cu	Ni	Cr	Mo	V	Nb	Ti	B	Total of Ca, REM, Mg, and Zr	N
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A1	0.139	0.57	0.48	0.0035	0.0005	0.061	0.17	0.21	1.43	0.63	0.009	0	0	0.0007	0	0.0031
A2	0.135	0.50	0.46	0.0015	0.0005	0.058	0.15	0.19	1.40	0.58	0.003	0	0	0.0007	0	0.0047
A3	0.139	0.55	0.47	0.0015	0.0005	0.057	0.17	0.22	1.45	0.61	0.007	0	0	0.0006	0	0.0040
A4	0.143	0.59	0.47	0.0015	0.0005	0.056	0.18	0.24	1.50	0.64	0.007	0	0	0.0007	0	0.0047
A5	0.139	0.55	0.47	0.0050	0.0021	0.058	0.15	0.29	1.40	0.60	0.027	0	0	0.0008	0	0.0047
A6	0.140	0.75	0.61	0.0050	0.0021	0.058	0.15	0.26	1.40	0.60	0.027	0	0	0.0007	0	0.0049
A7	0.140	0.55	0.46	0.0050	0.0022	0.057	0.15	0.21	1.41	0.60	0	0	0	0.0006	0	0.0049
A8	0.137	0.54	0.46	0.0050	0.0005	0.057	0.10	0.15	1.39	0.59	0	0	0	0.0007	0	0.0048
A9	0.140	0.55	0.47	0.0050	0.0033	0.056	0.10	0.16	1.40	0.60	0	0	0	0.0006	0	0.0046
A10	0.141	0.80	0.46	0.0050	0.0010	0.057	0.15	0.25	1.40	0.60	0.027	0	0	0.0008	0	0.0047
A11	0.134	0.67	0.59	0.0050	0.0010	0.055	0.10	0.16	1.40	0.45	0	0	0	0.0005	0	0.0050
A12	0.141	0.55	0.63	0.0050	0.0014	0.055	0.20	0.29	1.05	0.60	0	0	0	0.0005	0	0.0054
A13	0.140	0.54	0.46	0.0015	0.0020	0.057	0.15	0.25	1.39	0.60	0.027	0	0	0.0006	0	0.0051
A14	0.139	0.55	0.46	0.0050	0.0021	0.068	0.10	0.16	1.40	0.60	0	0	0	0.0007	0	0.0048

(continued)

Symbol of steel type	Composition (% by mass) Balance being iron and inevitable impurities														
	C	Si	Mn	P	S	Al	Cu	Ni	Cr	Mo	V	Nb	Ti	B	Total of Ca, REM, Mg, and Zr	N
A15	0.114	0.55	0.46	0.0015	0.0005	0.058	0.17	0.22	1.45	0.61	0.006	0	0	0.0006	0	0.0049
A16	0.134	0.55	0.46	0.0015	0.0005	0.058	0.17	0.22	1.43	0.62	0.005	0	0	0.0006	0	0.0048
A17	0.149	0.55	0.47	0.0015	0.0005	0.058	0.17	0.22	1.44	0.62	0.006	0	0	0.0006	0	0.0048
A18	0.137	0.54	0.47	0.0050	0.0005	0.060	0.17	0.21	1.44	0.60	0.005	0	0	0.0007	0	0.0047
A19	0.138	0.55	0.47	0.0070	0.0005	0.058	0.17	0.21	1.44	0.60	0.005	0	0	0.0005	0	0.0049
A20	0.140	0.56	0.47	0.0070	0.0015	0.057	0.17	0.21	1.44	0.61	0.005	0	0	0.0006	0	0.0048

[Table 1-2]

Symbol of steel type	Composition (% by mass) Balance being iron and inevitable impurities														
	C	Si	Mn	P	S	Al	Cu	Ni	Cr	Mo	V	Nb	Ti	B	Total of Ca, Mg, REM, and Zr	N
A21	0.139	0.55	0.45	0.0015	0.0005	0.040	0.17	0.21	1.44	0.62	0.006	0	0	0.0003	0	0.0055
A22	0.138	0.55	0.41	0.0015	0.0005	0.048	0.17	0.21	1.44	0.62	0.006	0	0	0.0007	0	0.0055
A23	0.141	0.55	0.45	0.0015	0.0005	0.070	0.17	0.21	1.44	0.62	0.006	0	0	0.0007	0	0.0055
A24	0.143	0.55	0.45	0.0015	0.0005	0.078	0.17	0.21	1.44	0.62	0.006	0	0	0.0007	0	0.0055
A25	0.140	0.55	0.47	0.0050	0.0018	0.056	0.08	0.16	1.39	0.60	0	0	0	0.0007	0	0.0043
A26	0.141	0.56	0.47	0.0050	0.0020	0.052	0.10	0.16	1.40	0.60	0	0	0	0.0008	0	0.0045
B1	0.157	0.56	0.47	0.0050	0.0019	0.055	0.10	0.16	1.40	0.60	0	0	0	0.0008	0	0.0044
B2	0.139	0.55	0.46	0.0050	0.0026	0.056	0.15	0.26	1.40	0.60	0.027	0	0	0	0	0.0047
B3	0.111	0.56	0.47	0.0050	0.0018	0.060	0.15	0.21	1.40	0.60	0.028	0.011	0	0.0007	0	0.0048
B4	0.109	0.55	0.46	0.0050	0.0016	0.057	0.15	0.21	1.40	0.60	0.028	0	0	0.0007	0	0.0047
B5	0.080	0.55	0.47	0.0050	0.0014	0.054	0.10	0.16	1.40	0.60	0	0	0	0.0007	0	0.0050
B6	0.140	0.74	0.61	0.0050	0.0019	0.057	0.15	0.26	1.39	0.60	0.027	0	0	0	0	0.0046
B7	0.109	0.54	0.47	0.0050	0.0019	0.054	0.10	0.16	1.39	0.59	0	0	0	0.0006	0	0.0049
B8	0.077	0.55	0.46	0.0050	0.0013	0.055	0.09	0.16	1.40	0.59	0	0	0	0	0	0.0040
B9	0.137	0.55	0.46	0.0050	0.0018	0.057	0.10	0.26	1.40	0.60	0	0	0.014	0.0006	0	0.0046
B10	0.138	0.55	0.47	0.0050	0.0017	0.056	0.10	0.16	1.41	0.60	0	0.010	0	0.0006	0	0.0048
B11	0.141	0.55	0.47	0.0150	0.0013	0.056	0.10	0.16	1.40	0.60	0	0	0	0.0007	0	0.0043
B12	0.138	0.55	0.46	0.0150	0.0019	0.058	0.10	0.16	1.40	0.60	0	0	0	0	0	0.0048
B13	0.139	0.55	0.46	0.0015	0.0018	0.055	0.10	0.15	1.40	0.60	0	0	0	0	0	0.0044
B14	0.138	0.55	0.46	0.0050	0.0019	0.041	0.10	0.16	1.40	0.59	0	0	0	0.0002	0	0.0053
B15	0.080	0.55	0.46	0.0050	0.0025	0.059	0.15	0.21	1.40	0.60	0.027	0	0	0.0009	0	0.0044
B16	0.160	0.55	0.46	0.0050	0.0012	0.059	0.40	0.40	1.40	0.60	0.027	0	0	0.0006	0	0.0047

[Table 2-1]

Test No.	Symbol of steel type	Ac_1 point	Thickness (mm)	Quenching		Tempering		
				Temperature (°C)	Time (min.)	Temperature (°C)	Time (min.)	P_T value
1	A1	774	35	930	25	760	25	20.27
2	A1	774	63	930	25	760	50	20.58
3	A1	774	63	930	30	730	30	19.76
4	A1	774	94	930	35	724	12	19.24
5	A1	774	94	930	35	760	20	20.17
6	A1	774	94	930	35	710	20	19.19
7	A1	774	94	915	55	730	25	19.68
8	A1	774	94	930	25	730	25	19.68
9	A1	774	94	930	55	730	25	19.68
10	A1	774	94	930	5	730	25	19.68
11	A1	774	94	930	35	760	70	20.73
12	A2	772	93	930	30	730	25	19.68
13	A3	774	93	930	30	730	25	19.68
14	A4	776	93	930	30	730	25	19.68
15	A5	772	93	930	30	730	25	19.68
16	A6	775	93	930	30	730	25	19.68
17	A7	773	93	930	30	730	25	19.68
18	A8	774	93	930	30	730	25	19.68
19	A9	774	93	930	30	730	25	19.68
20	A10	778	93	930	30	730	25	19.68
21	A11	775	93	930	30	730	25	19.68
22	A12	767	93	930	30	730	25	19.68
23	A13	772	93	930	30	730	25	19.68
24	A14	774	93	930	30	730	25	19.68
25	A15	774	93	930	30	730	35	19.83
26	A16	774	93	930	30	730	25	19.68

[Table 2-2]

Test No.	Symbol of steel type	Ac_1 point	Thickness (mm)	Quenching		Tempering		
				Temperature (°C)	Time (min.)	Temperature (°C)	Time (min.)	P_T value
27	A17	774	93	930	30	730	25	19.68
28	A18	774	93	930	30	730	25	19.68
29	A19	774	93	930	30	730	25	19.68
30	A20	774	93	930	30	730	25	19.68
31	A21	774	93	930	30	730	25	19.68

(continued)

Test No.	Symbol of steel type	Ac_1 point	Thickness (mm)	Quenching		Tempering		
				Temperature (°C)	Time (min.)	Temperature (°C)	Time (min.)	P_T value
32	A22	775	93	930	30	730	25	19.68
33	A23	774	93	930	30	730	25	19.68
34	A24	774	93	930	30	730	25	19.68
35	A25	774	93	930	30	730	25	19.68
36	A26	774	93	930	30	760	25	20.27
37	B1	774	93	930	30	730	25	19.68
38	B2	773	93	930	30	730	25	19.68
39	B3	773	93	930	30	730	25	19.68
40	B4	773	93	930	30	730	25	19.68
41	B5	774	93	930	30	730	25	19.68
42	B6	774	93	930	30	730	25	19.68
43	B7	773	93	930	30	730	25	19.68
44	B8	774	93	930	30	730	25	19.68
45	B9	773	93	930	30	730	25	19.68
46	B10	774	93	930	30	730	25	19.68
47	B11	774	93	930	30	730	25	19.68
48	B12	774	93	930	30	730	25	19.68
49	B13	774	93	930	30	730	25	19.68
50	B14	774	93	930	30	730	25	19.68
51	B15	773	93	930	30	730	25	19.68
52	B16	771	93	930	30	730	25	19.68

[Table 3-1]

Test No.	Structure		Effective grain size D (μm)	Maximum carbide size d (μm)	D/d	HBW Ave	YS (MPa)	TS (MPa)	vE_{-38} (J)
	B+M (area %)	F (area %)							
1	100	0	12.0	0.50	24.00	190	414	552	439
2	100	0	12.0	0.70	17.14	178	398	545	120
3	100	0	12.0	0.50	24.00	185	370	554	422
4	100	0	15.0	0.50	30.00	197	412	573	188
5	100	0	16.0	0.60	26.67	180	384	561	171
6	100	0	14.0	0.40	35.00	216	412	575	209
7	100	0	16.0	0.50	32.00	185	398	566	149
8	100	0	16.0	0.50	32.00	190	418	564	377
9	100	0	16.0	0.60	26.67	189	395	561	251

(continued)

Test No.	Structure		Effective grain size D (μm)	Maximum carbide size d (μm)	D/d	HBW Ave	YS (MPa)	TS (MPa)	vE_{-38} (J)
	B+M (area %)	F (area %)							
10	90	10	35.0	0.50	70.00	180	386	545	56
11	100	0	16.0	0.85	18.82	168	306	510	22
12	100	0	26.0	0.50	52.00	181	381	546	255
13	100	0	21.6	0.50	43.20	192	386	555	269
14	100	0	19.0	0.50	38.00	188	389	564	320
15	100	0	18.0	0.50	36.00	190	396	558	420
16	100	0	15.3	0.42	36.43	199	408	579	178
17	100	0	17.8	0.50	35.60	186	409	570	215
18	100	0	24.0	0.50	48.00	175	405	562	337
19	100	0	23.5	0.50	47.00	181	384	548	128
20	100	0	18.0	0.50	36.00	192	407	584	202
21	100	0	26.0	0.50	52.00	186	396	558	168
22	100	0	24.0	0.50	48.00	182	387	564	165
23	100	0	20.0	0.50	40.00	186	393	557	277
24	100	0	23.0	0.50	46.00	181	391	548	165
25	100	0	24.0	0.45	53.33	184	369	537	256
26	100	0	21.0	0.50	42.00	188	374	546	348

[Table 3-2]

Test No.	Structure		Effective grain size D (μm)	Maximum carbide size d (μm)	D/d	HBW Ave	YS (MPa)	TS (MPa)	VE_{-38} (J)
	B+M (area %)	F (area %)							
27	100	0	18.5	0.50	37.00	192	390	566	259
28	100	0	21.0	0.50	42.00	182	370	548	277
29	100	0	22.0	0.50	44.00	185	379	551	272
30	100	0	21.0	0.50	42.00	185	384	550	176
31	100	0	18.0	0.50	36.00	181	374	548	346
32	100	0	20.0	0.50	40.00	182	380	553	337
33	100	0	21.0	0.50	42.00	181	380	554	410
34	100	0	19.0	0.50	38.00	188	397	565	356
35	100	0	22.6	0.50	45.20	189	389	555	146
36	100	0	22.0	0.60	36.67	173	364	535	109
37	100	0	35.0	0.60	58.33	201	395	564	86
38	100	0	37.9	0.50	75.80	185	380	544	8
39	100	0	40;9	0.50	81.80	185	424	560	9

(continued)

Test No.	Structure		Effective grain size D (μm)	Maximum carbide size d (μm)	D/d	HBW Ave	YS (MPa)	TS (MPa)	VE_{-38} (J)
	B+M (area %)	F (area %)							
40	100	0	31.6	0.50	63.20	182	391	534	28
41	70	30	43.8	0.40	109.50	172	347	497	34
42	100	0	40.2	0.50	80.44	193	389	567	13
43	100	0	45.0	0.50	90.00	185	368	521	14
44	100	0	45.0	0.50	90.00	171	327	487	56
45	100	0	42.0	0.50	84.00	199	397	554	11
46	80	20	43.0	0.50	86.00	211	413	567	12
47	100	0	20.0	0.50	40.00	181	391	556	56
48	100	0	42.0	0.50	84.00	182	373	545	9
49	100	0	45.0	0.50	90.00	177	367	538	8
50	100	0	30.0	0.50	60.00	180	380	539	25
51	100	0	25.0	0.40	62.50	170	372	512	11
52	100	0	14.0	0.60	23.33	198	429	595	91

[0074] Table 1-1, Table 1-2, Table 2-1, Table 2-2, Table 3-1, and Table 3-2 will reveal the followings. Samples Nos. 1 to 5, 7 to 9, and 12 to 36 are produced under defined conditions using steels satisfying the composition defined in the present invention. Therefore, the thus obtained steel plates exhibited excellent workability and the thus obtained steel member had desired structure and exhibited excellent strength and toughness in the thicknesswise central portion.

[0075] Meanwhile, regarding examples other than the above, either composition or manufacturing conditions deviate(s) from the defined range or condition, thus failing to ensure the workability of the steel plate, or either tensile properties or impact properties in the thicknesswise central portion are inferior.

[0076] Sample No. 6 satisfies the composition but is not sufficiently tempered because of excessively low P_T value during tempering, leading to high Brinell hardness, i.e., inferior workability. Meanwhile, sample No. 11 satisfies the composition but causes coarsening of carbide because of excessively high P_T value during tempering, leading to degradation of properties.

[0077] Sample No. 10 satisfies the composition but is not sufficiently quenched because of too short heating time of quenching, so that D/d exceeds the upper limit, leading to inferior toughness.

[0078] Sample No. 37 contains excessive C, thereby causing degradation of the toughness, leading to high Brinell hardness and inferior workability.

[0079] Samples Nos. 38, 42, and 49 do not contain B, thereby increasing D/d, leading to inferior toughness. Sample No. 48 does not contain B, thereby increasing D/d, and contain excessive P, leading to inferior in toughness.

[0080] Samples No. 39 and No. 46 contain excessive Nb, thereby refining prior austenite (γ) grains during quenching, thus failing to obtain sufficient hardenability, leading to increased D/d and inferior toughness. In sample No. 46, the workability was also degraded.

[0081] Samples Nos. 40 and 43 are lacking in C content, thus failing to ensure sufficient hardenability, leading to increased D/d and inferior toughness. Sample No. 41 is lacking in C content, thus failing to ensure desired strength due to formation of a large amount of ferrite, leading to increased D/d and inferior toughness. Sample No. 44 is lacking in C content and does not contain B, thus failing to ensure sufficient hardenability, leading to low strength, increased D/d, and degraded toughness. Sample No. 51 is lacking in C content, thus failing to ensure desired toughness due to small carbide size and increased D/d.

[0082] Sample No. 45 contains excessive Ti, thus failing to obtain sufficient hardenability due to refined prior austenite (γ) grains during quenching, leading to increased D/d and inferior toughness.

[0083] Sample No. 47 was inferior in toughness because of excessive P content.

[0084] Sample No. 50 is lacking in B content, thus failing to achieve sufficient hardenability, leading to degradation of the toughness.

[0085] Sample No. 52 contains excessive Cu and Ni and contains excessive C, causing degradation of the toughness.

[0086] Fig. 1 is a graph showing the relationship between D/d and Charpy absorbed energy at -38°C using data in Table 2-1, Table 2-2, Table 3-1, and Table 3-2. As is apparent from this graph, the adjustment of D/d to 54 or less enables ensuring sufficiently excellent toughness. As mentioned above, samples No. 47 and 52 in Fig. 1 are examples in which the toughness was degraded because of deviation of the composition from the defined range, although D/d satisfies the scope of the present invention.

Claims

1. A steel member having a composition comprising, in % by mass:

C: 0.110% or more and 0.15% or less,
Si: 0.50% or more and 0.80% or less,
Mn: 0.40% or more and 0.65% or less,
P: exceeding 0% and 0.0070% or less,
S: exceeding 0% and 0.0070% or less,
Al: 0.030% or more and 0.080% or less,
Cu: 0.05% or more and 0.20% or less,
Ni: 0.05% or more and 0.30% or less,
Cr: 1.05% or more 1.50% or less,
Mo: 0.45% or more and 0.65% or less,
N: 0.0030% or more and 0.0070% or less,
B: 0.0003% or more and 0.0010% or less, and
V: 0% or more and 0.030% or less,

wherein Nb content is suppressed to 0.005% or less, Ti content is suppressed to 0.001% or less, and the total content of Ca, Mg, REM, and Zr is suppressed to 0.0010% or less, the remainder consists of iron and inevitable impurities,
a thickness is 100 mm or less, and
a structure in a thicknesswise central portion of the steel member satisfies the following (a) and (b), and Charpy absorbed energy at -38°C is 100 J or more:

(a) the structure is at least one of tempered bainite and tempered martensite, and
(b) a value represented by D/d is 54 or less, where D is an average equivalent circle diameter of crystal grains surrounded by large angle grain boundaries with crystal misorientation of 15° or more between two adjacent crystal grains, and d is a maximum diameter of grain boundary carbide.

2. A steel plate used for manufacturing the steel member according to claim 1, which has a composition comprising, in % by mass,

C: 0.110% or more and 0.15% or less,
Si: 0.50% or more and 0.80% or less,
Mn: 0.40% or more and 0.65% or less,
P: exceeding 0% and 0.0070% or less,
S: exceeding 0% and 0.0070% or less,
Al: 0.030% or more and 0.080% or less,
Cu: 0.05% or more and 0.20% or less,
Ni: 0.05% or more and 0.30% or less,
Cr: 1.05% or more 1.50% or less,
Mo: 0.45% or more and 0.65% or less,
N: 0.0030% or more and 0.0070% or less,
B: 0.0003% or more and 0.0010% or less, and
V: 0% or more and 0.030% or less,
wherein Nb content is suppressed to 0.005% or less, Ti content is suppressed to 0.001% or less, the total content of Ca, Mg, REM, and Zr is suppressed to 0.0010% or less, and the remainder consists of iron and inevitable impurities, and wherein a thickness of the steel plate is 100 mm or less.

3. A method for manufacturing the steel plate according to claim 2, which comprises hot-rolling a steel slab having the composition according to claim 2; performing quenching under a condition of a heating temperature of 910°C or higher and 940°C or lower and a holding time at the heating temperature of 25 minutes or more and 60 minutes or less; and, after the quenching, performing tempering at a heating temperature of 620°C or higher and an Ac_1 point or lower under a condition of the heating temperature and a heating time such that a P_T value represented by the following equation (1) is 19.2 or more and 20.6 or less:

$$P_T \text{ value} = T_T \times (20 + \log t_T) \times 10^{-3} \qquad (1)$$

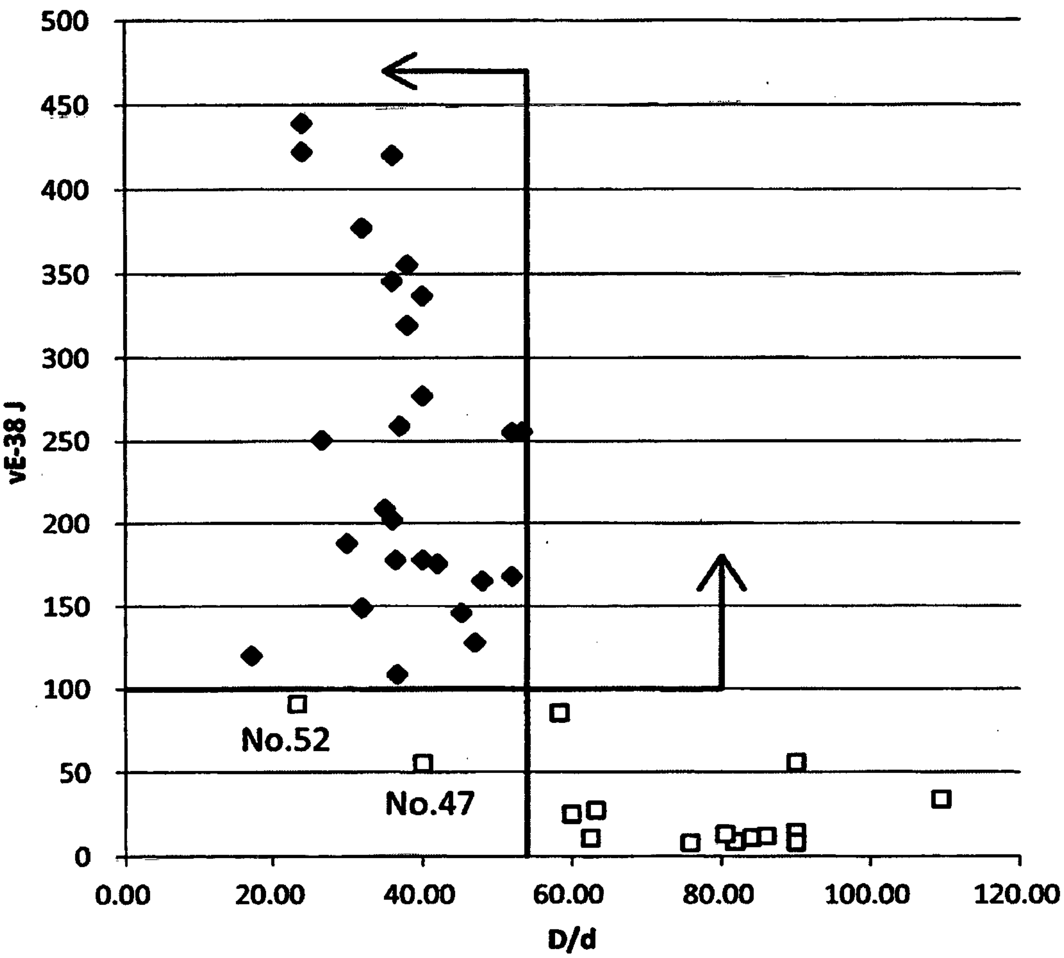
where T_T denotes heating temperature (K) of tempering, and t_T denotes heating time (hr) of tempering.

4. A method for manufacturing the steel member according to claim 1, which comprises welding using the steel plate according to claim 2; and performing a post weld heat treatment under a condition of a heating temperature and a heating time such that a P_{PWHT} value represented by the following equation (2) is 20 or more:

$$P_{PWHT} \text{ value} = T_{PWHT} \times (20 + \log t_{PWHT}) \times 10^{-3} \qquad (2)$$

where T_{PWHT} denotes heating temperature (K) of post weld heat treatment, and t_{PWHT} denotes heating time (hr) of post weld heat treatment.

Fig. 1



500
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250
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150
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50
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vE-38 J
No.52
No.47
0.00
20.00
40.00
60.00
80.00
100.00
120.00
D/d

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/082223

A. CLASSIFICATION OF SUBJECT MATTER
C22C38/00(2006.01)i, *C21D8/02*(2006.01)i, *C21D9/00*(2006.01)i, *C21D9/50*(2006.01)i, *C22C38/54*(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C22C38/00-38/60, C21D8/00-8/10, C21D9/00, C21D9/50

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2017
Kokai Jitsuyo Shinan Koho	1971-2017	Toroku Jitsuyo Shinan Koho	1994-2017

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2014-095130 A (Kobe Steel, Ltd.), 22 May 2014 (22.05.2014), paragraphs [0011] to [0088] & EP 2918694 A1 paragraphs [0011] to [0087]	1-4
A	JP 2004-143504 A (Nippon Steel Corp.), 20 May 2004 (20.05.2004), (Family: none)	1-4
A	JP 2014-194042 A (JFE Steel Corp.), 09 October 2014 (09.10.2014), & US 2016/0076118 A1 & EP 2980250 A1	1-4
A	JP 2013-108168 A (JFE Steel Corp.), 06 June 2013 (06.06.2013), (Family: none)	1-4

☒ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
05 January 2017 (05.01.17)	24 January 2017 (24.01.17)

Name and mailing address of the ISA/	Authorized officer
Japan Patent Office 3-4-3,Kasumigaseki,Chiyoda-ku, Tokyo 100-8915,Japan	Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/082223

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2011/099408 A1 (Nippon Steel Corp.), 18 August 2011 (18.08.2011), & JP 4874434 B1 & CN 102666885 A	1-4

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